WHITE **PAPER**

Multiband Active Antenna Tuner for Cellular IoT Applications

This white paper discusses related design challenges and solutions for developing a multiband active antenna tuner for cellular internet of things (IoT) massive machine-type communications (mMTC) applications.

Contents

Design Overview

With the release of each new generation of wireless technology since the introduction of the portable phone in the early 1980s, mobile communications have progressed exponentially. Each generation has launched new services and business opportunities, leading up to what is being referred to as the "third wave" of communications. The evolution made possible through 5G and future 6G technology will support even more new services for industry and society, well into the 2030s and beyond (Figure 1).

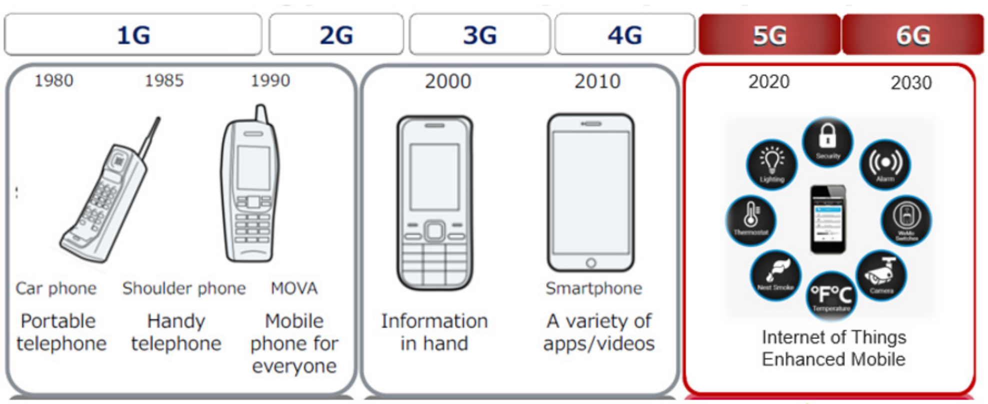

Figure 1: Generations of mobile communications technology and services

5G represents the first step towards this next wave of services with expanded connectivity and a significant upgrade in multimedia capabilities combined with artificial intelligence (AI) and IoT. 5G will be the first generation of mobile communications to utilize millimeter-wave (mmWave) band frequencies, supporting bandwidths of several hundred megahertz (MHz), which will actualize ultra-high-speed wireless data communications of many gigabits per second.

The Third Wave of Wireless Communications

5G and subsequent systems will close the gap between the physical and cyber worlds. Today, mobile consumers use wireless connectivity to access the web from almost any location. In the future, high-speed coverage will be more widespread and faster, and there will be greater emphasis on uplinking information from real-world events and human, and/or IoT activity to the internet. mMTC provides connectivity to a huge number of devices whose traffic profile is typically a small amount of data spread sporadically. So, latency and throughput are not a big concern: The main concern is the optimal power utilization of those devices because they are battery powered and the battery life is expected to exceed 10 years.

6G will implement many different technologies, including new topologies of overlapping cells with distributed networks of beamforming antennas controlled by AI and ML to select optimum transmission paths dynamically. Previous cellular communications were based on networks of hexagonal cells spaced far enough apart to avoid signal interference with neighboring cells. 6G may employ a spatially non-orthogonal, overlapped, and dynamic topology to increase path selection. Beam control through AI/ML will help reduce intercell interference (ICI) at a cost of complexity. This architecture will also require new antenna designs, conformal as well as phased arrays. For more bandwidth, 6G is expected to utilize higher mmWave frequencies from 94GHz to 3THz.

The move to higher frequency bands will help reduce the size of these antennas, making efforts to shrink component footprints easier; however, the antennas, feed networks, and package interconnects will be more susceptible to parasitics and unintended coupling (crosstalk), requiring rigorous EM analysis and design verification at a system level, as shown in Figure 2.

IC PKG Test Cases	CPU Cores	Clarity	Legacy	Performance Gain	Clarity Memory Requirement	Clarity Memory Reduction
Flipchip PDN	32	4h	41.6h	10.4X	42GB	84%

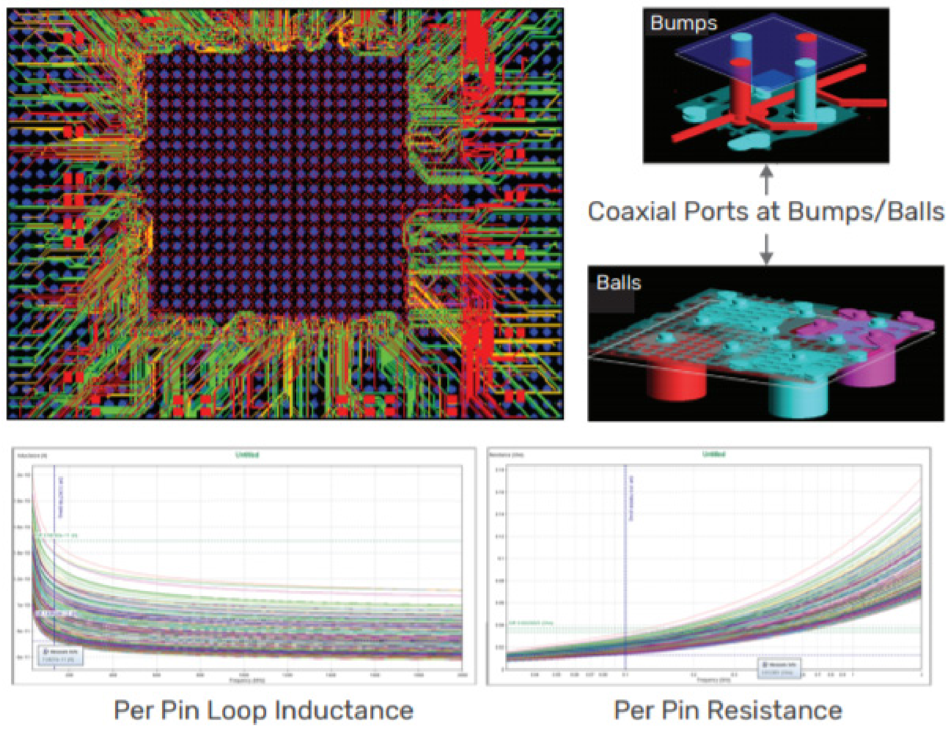

Figure 2: Cadence Clarity™ 3D Solver (finite element method [FEM]/finite difference time domain [FDTD]) software addresses critical interconnect modeling of large-scale, integrated RF/mixed-signal electronic systems powering third-wave communications

New functionalities in spatial multiplexing and massive multiple-in-multiple-out (MIMO) are under investigation including the use of reflective surfaces and metamaterials to manage signal propagation in crowded urban environments with limited line of sight. Coverage will be expanded through space, sea, and high-altitude drones.

Lastly, much of the focus will be on physical design of radio access front-ends. Strategic design partitioning, leveraging of optimal semiconductor processes, and multi-fabric assemblies will undoubtedly be utilized, calling for a range of simulation technologies, design and manufacturing flows, and tool interoperability. All these trends were anticipated in the development of the Cadence® Intelligent System Design™ strategy to support codesign and co-optimization of next-generation wireless electronic systems across multiple domains, including RF, analog, and digital simulation, aided by large-scale electromagnetic (EM) and thermal analysis, and robust design verification and signoff.

Cellular IoT Applications

One goal of 5G mMTC is to provide scalable connectivity for a large number of IoT devices (Figure 3). The devices themselves support various sensing and actuation functionality. They are relatively low in complexity but battery-constrained in order to support years of field operations without servicing. To share data to the network, mMTC is uplink-centric with relatively low data rates, optimized for small packets (down to a few bytes). Uplink communication is based on sporadic user (event-driven) activity or scheduled transmissions.

Today's cellular IoT (cIoT) devices are supported through narrowband IoT (NB-IoT) and LTE Category M-1 (Cat M-1) networks, which currently offer support for 40,000-50,000 devices per cell. 5G aims to support up to 1M devices per cell. Being tied to a cellular network gives them greater range than low-power wide area networks (WAN), so they are applicable to mobile applications, such as in-transit asset tracking. As sensing devices without the need for time-sensitive information, mMTC networks can be latency agnostic.

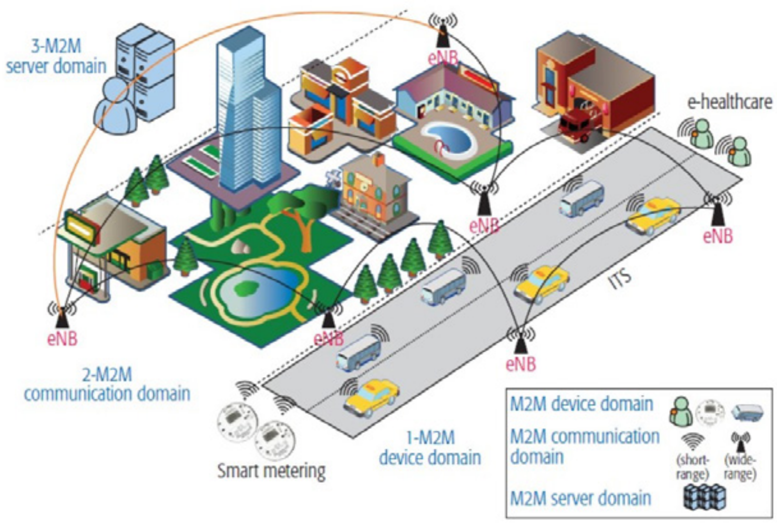

Figure 3: mMTC provides scalable connectivity for a large number of IoT devices

Fractus Antennas, a leader in the design and manufacture of miniature antennas for smartphones, short-range wireless, and connected IoT devices, uses Cadence AWR® software to integrate antennas into these products. With the network synthesis wizard option available in the Cadence AWR Microwave Office® software, Fractus Antenna engineers can easily implement a suitable matching network for the desired single-band, multiband, or broadband operations. This ensures maximum power delivered to the antenna for devices that require low power consumption without sacrificing range (coverage).

Fractus Antennas designed a multiband active antenna tuner for a battery-operated prototyping platform for cellular IoT (cIoT) from Nordic Semiconductor. The Nordic Thingy:91 prototyping board in Figure 4 is built around a low-power system in package (SiP) module (nRF9160) with integrated LTE-M/NB-IoT modem and GPS technology. Certified for a broad range of LTE bands globally, the Nordic Thingy:91 can be used just about anywhere in the world. The cellular communication can be interleaved with GPS positioning acquisition for sophisticated asset tracking.

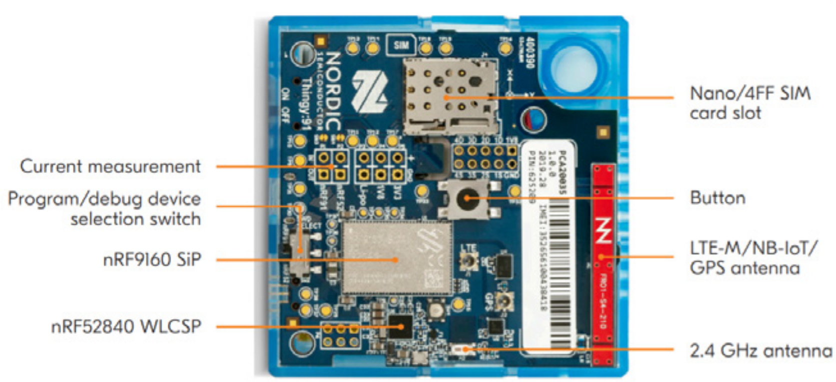

Figure 4: Nordic Thingy:91 prototyping board for cIoT asset-tracking applications (image courtesy of Nordic Semiconductor)

The cIoT module and prototyping board offer six bands of operation, including GPS, supported by the antenna and the band-specific impedance matching networks developed by Fractus Antenna. The RF section of the board includes the IoT module from Nordic Semiconductor and two single-pole, eight-throw switches from Qorvo, which allow the signal to pass through different matching circuits dependent on the desired operating band and the Fractus Antenna (Figure 5).

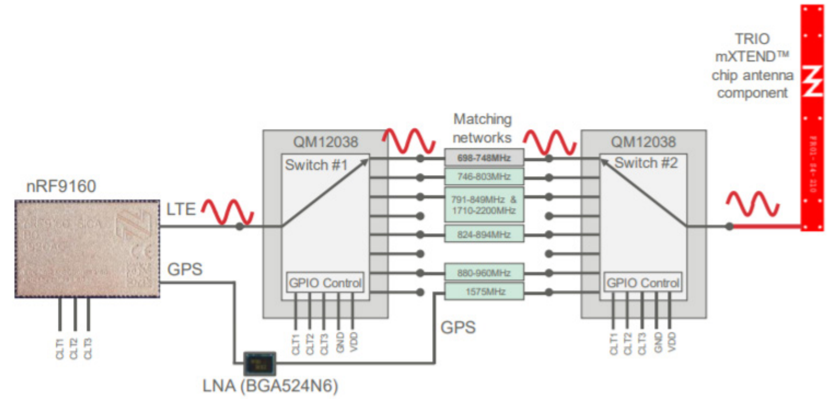

Figure 5:. Block diagram of cIoT module and active antenna tuner for six-band operations

The derived matching circuit topologies and bill of materials (BOM) are shown in Table 1 and the resulting antenna efficiency response versus frequency for different switch settings is shown in Figure 6.

STATE	Frequency band	Matching Network: Component	Value	Part Number
RF5	698-748MHz & 1710-2200MHz	Z_1	5.1nH	LQW03AW5N1J00
		Z2 (C10)	5.5pF	GJM0332C1H5R5WB01
RF7	746-803MHz& 1710-2200MHz	Z_1	4.7nH	LQW03AW4N7J00
		Z_2	0Ω	-
RF8	791-849MHz& 1710-2200MHz	Z_1	9.2pF	GJM0332C1E9R2WB01
		Z_2	6.2nH	LQW03AW6N2J00
RF3	824-894MHz	Z_1	1.5pF	GJM0334C1E1R5WB01
RF1	880-960MHz	Z_1	2.5pF	GJM0335C1E2R5WB01
		Z_2	Open circuit	-
RF4	GPS (1575MHz)	Z_1	2.2nH	LQW15AN2N2C10
		Z_2	2.5pF	GJM1555C1H2R5WB01
RF2&6	available for other bands	empty		

Table 1. Fractus Antenna matching circuit topologies and BOM

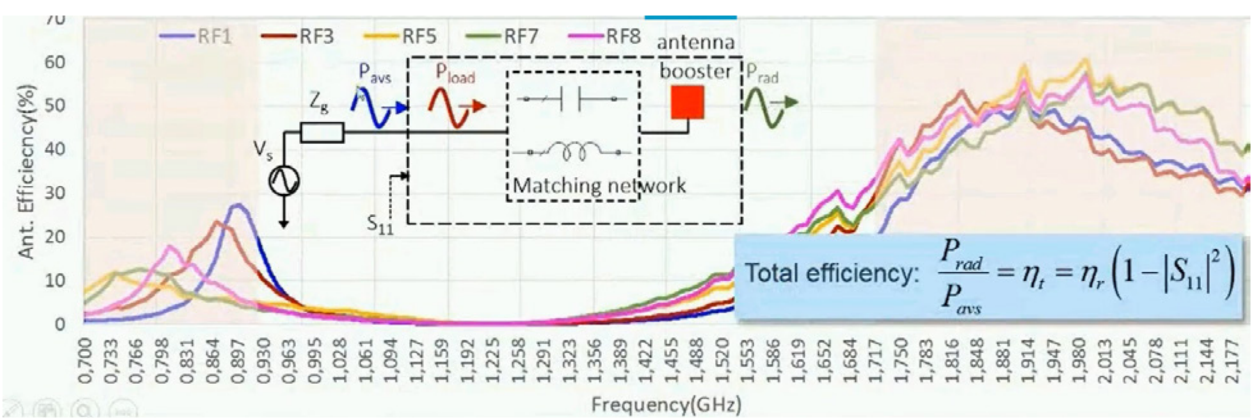

Figure 6: Antenna efficiency response vs. frequency for different switch settings

The impedance matching networks are developed with the AWR network synthesis wizard. This goal-driven synthesis tool creates matching networks according to simulation measurements and user-specified performance goals such as small-signal return loss or nonlinear amplifier behavior (output power [Pout], power-added efficiency [PAE], etc.) from load-pull performance contours. The synthesis engine uses a proprietary, genetic optimization algorithm and heuristics to identify candidate matching networks, addressing challenging impedance matching problems across multiple performance goals and frequency bands.

The RF designer specifies which component types, such as an inductor, capacitor, and transmission line, can appear in a given series or shunt configuration, thereby managing the topology as well as allowing the user to constrain component parameter values to reflect manufacturing tolerances. This capability accelerates impedance matching, providing RF engineers with a greater number of viable network candidates through rapid design space exploration, (Figure 7).

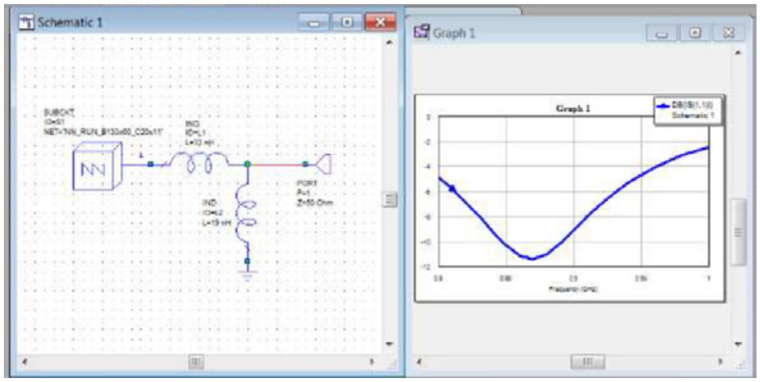

Figure 7: Simple two-element (ideal inductors) matching circuit and resulting return loss of matched antenna component

Synthesized networks can be based on models from the AWR Microwave Office software's ideal parts library, vendor component libraries, and microstrip transmission lines using substrate definitions in the given project. The user can then specify which candidate networks to import directly into the AWR Microwave Office project. Engineers at Fractus Antenna use network synthesis to achieve the desired in-band return loss for their surface mount antenna model, which is available as a component model (S-parameters) in the AWR Microwave Office software's standard vendor library. The designer places this antenna component into a schematic subcircuit and develops an impedance matching network to optimize the subcircuit's return loss, thereby maximizing antenna efficiency, the ratio of power radiated to power supplied to the antenna.

In addition to developing the matching network, AWR software and Cadence's AWR AXIEM® 3D planar EM analysis can be used to further characterize the board to ensure the matching circuit works properly when incorporated into a larger structure with likely parasitics. To do this, the PCB import wizard in the Cadence AWR Design Environment® platform was used to import the metal layers, which are available as Gerber layout files from the manufacturer's website. The four individual metal layers were used to create an AWR AXIEM analysis subcircuit combined into a four-layer structure, shown in Figure 8.

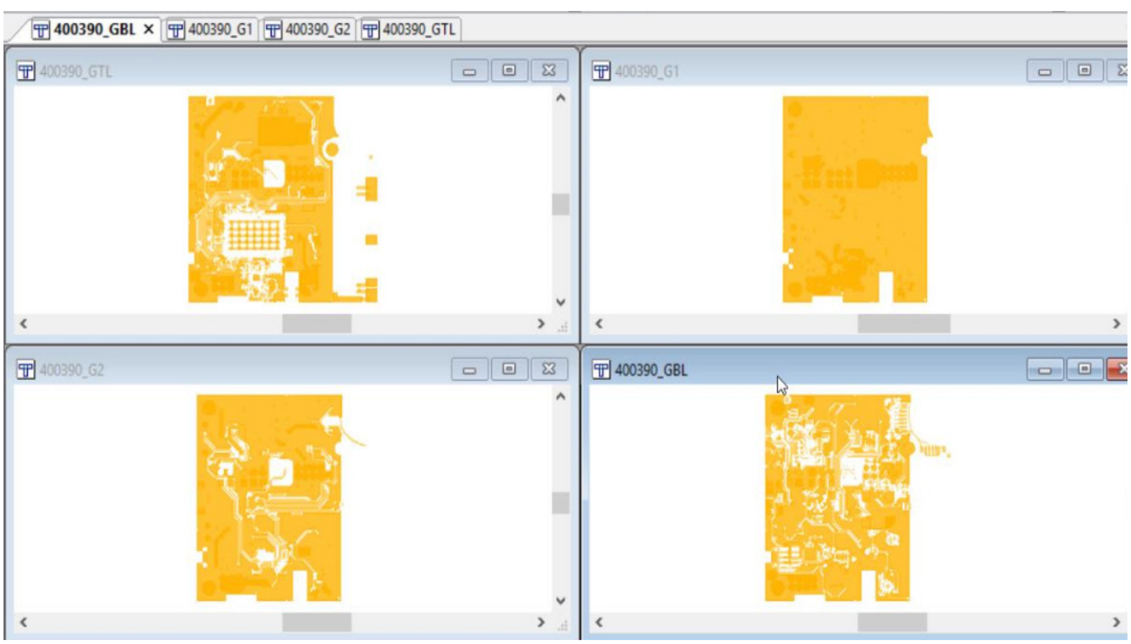

Figure 8: Four-layer (2 signal, 2 ground planes) Gerber file layouts imported into AWR Design Environment platform

Figure 9 shows the structure in the AWR AXIEM analysis with defined edge ports and annotation of the automatic adaptive meshing used to solve and extract the S-parameters. Shape pre-processing rules were applied to simplify the via structures for faster simulation without sacrificing accuracy. This EM structure size was approximately 84k unknowns and was easily solved in about 10 minutes on a single machine. Looking closely at the mesh, one can see the hybrid meshing technology employed by AWR AXIEM analysis to ensure fast and accurate results.

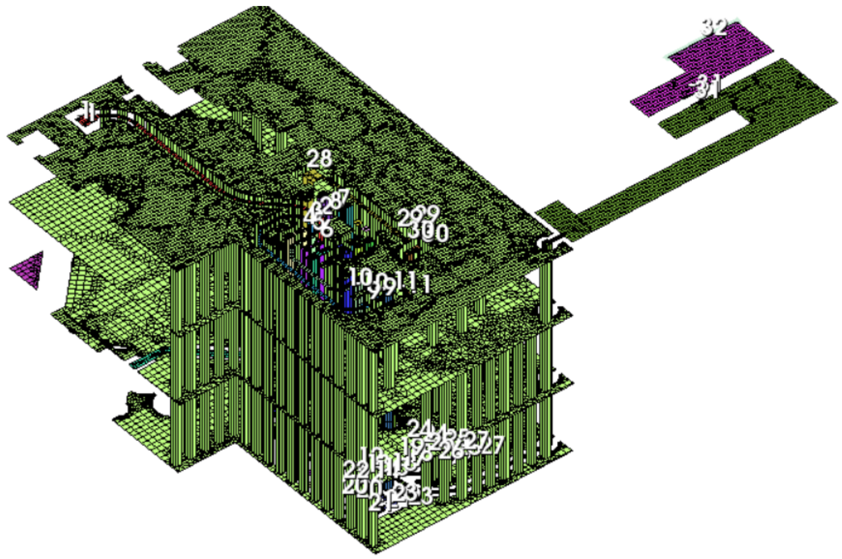

Figure 9: Exploded view of Thingy:91 structure (RF section) in AWR AXIEM analysis with defined edge ports and annotation showing the automatic adaptive meshing

With the AWR AXIEM analysis fully integrated within the AWR Microwave Office software's circuit simulator, EM/circuit co-design is achieved by simply placing the subcircuit containing the EM structure into an AWR Microwave Office schematic with other circuit-based components (Figure 10).

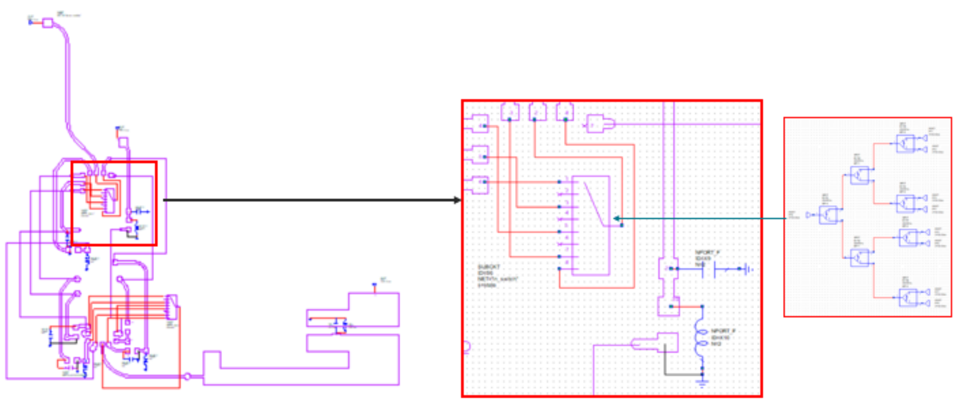

Figure 10: Multiport EM subcircuit populated with lumped-element components from the vendor library and parameterized single pole, eight-throw switches for EM/circuit co-design

A standard script is available to create a schematic symbol based on physical layout details of the structure, helping engineers manage port connections for structures with many ports. This visual aid helps designers insert circuit components in their correct location on the board. In this example, an ideal switch with parameterized switch states was implemented in AWR Microwave Office software. This allows the designer to toggle through different impedance matching networks by adjusting the switch position, shown in Figure 11.

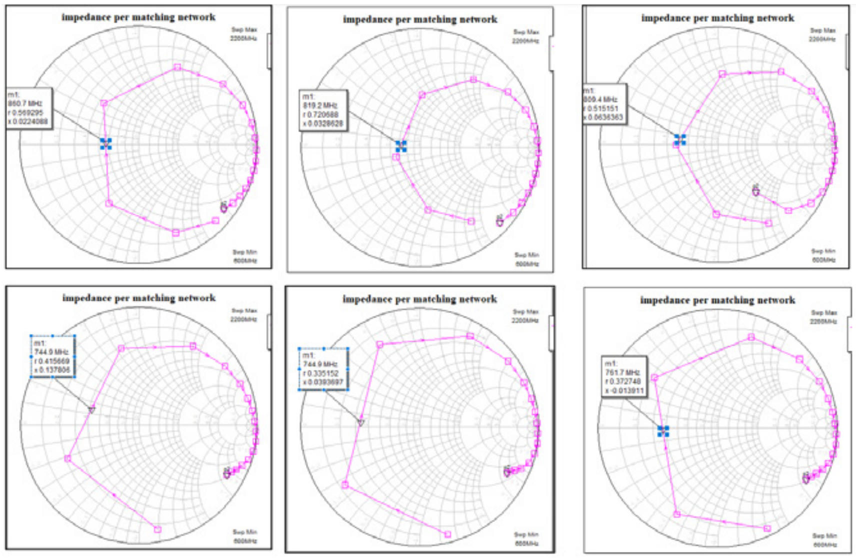

Figure 11. Input impedance (S11) vs. switch position looking into the matching network implemented on a four-layer cIoT prototyping board terminated with the Fractus Virtual Antenna

This antenna manufacturer also supplies measured antenna gain information, which could be used by the antenna model in AWR Visual System Simulator™ (VSS) communications and radar systems design software as part of a link budget analysis when defining component specifications and validating system designs based on presumed path losses, receiver sensitivity, and regulated transmitter power levels (or effective isotropic radiated power [EIRP]).

Furthermore, AWR VSS software offers several preconfigured NB-IoT testbenches that allow the designer to examine various figures of merit including the modulated spectrum, the IQ constellation of the transmitted and demodulated signals, bit or block error rates, and throughput (Figure 12). By replacing the default device under test in this project with a single component or an entire RF link including the antenna and perhaps channel modeling of the propagation losses, the AWR VSS software's NB-IoT testbench lets engineers sweep various parameters, such as input power, or toggle different NB-IoT subcarrier modulation schemes (ϖ/2 BPSK or π/4 QPSK) to investigate the impact on performance, such as error vector magnitude (EVM).

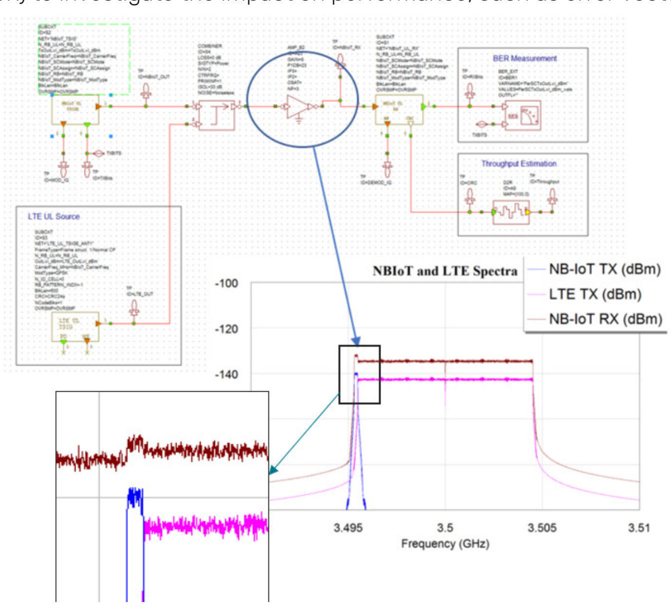

Figure 12. NB-IoT uplink to enhanced NB (eNB) RX testbench in AWR VSS software

With the RF design, analysis, and verification complete and EM, circuit, and system-level performance criteria met, the RFIP can be passed along to the layout team for any additional design integration, design rule check (DRC)/layout vs. schematic (LVS), and final signoff. To address the manufacturing flow, layouts from AWR Microwave Office software can be exported as a drawing interchange format (DXF) file (as well as GDSII and Gerber), which can then be imported into Cadence Allegro® PCB Designer software for any further development (Figure 13).

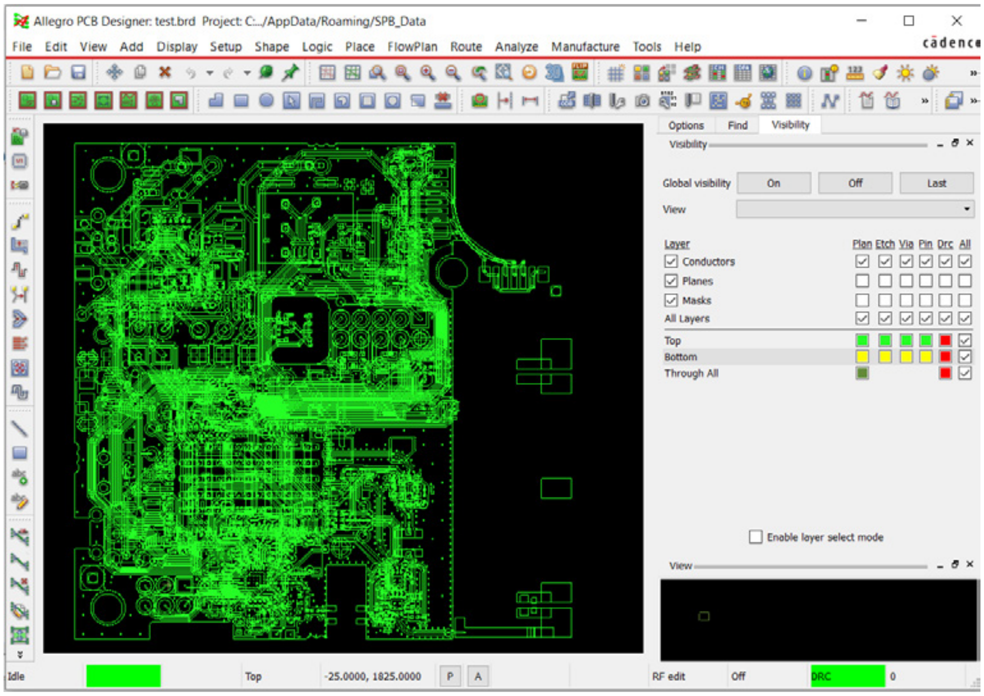

Figure 13. Complete cIoT board imported into Allegro PCB Designer from AWR Design Environment platform's DXF export

Conclusion

Next-generation communication systems targeting 5G/6G functionality will provide massive connectivity to the internet with extreme capacity, coverage, reliability, and ultra-low latency, enabling a wide range of new services and business opportunities. The anticipated performance will be made possible through a range of innovative technologies, implemented though complex RF front-end architectures and highly integrated multi-fabric electronics. RF to mmWave design and multi-fabric design and manufacturing software will be critical to the development of these technologies.

To power the technologies and products that will realize 5G/6G performance across chips, IP, packages, and PCBs, Cadence has developed the Intelligent System Design strategy for delivering its world-class computational software capabilities across all aspects of the design of electronic systems. This white paper has presented several examples of how Cadence is uniquely positioned with deep expertise and pivotal leadership in computational software, along with the broadest, most integrated design solution, to bring the Intelligent System Design strategy to the communication products of the future.